SOME UNCERTAINTIES IN THE DERIVATION OF RATES OF DENUDATION FROM THERMOCHRONOLOGIC DATA

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ABSTRACT

Low-temperature thermochronology, such as that provided by apatite fission-track analysis, provides a valuable means of establishing the timing of major denudational events and associated rates of denudation over geological time-scales of 10^6–10^8 Ma. Care must be taken, however, in deriving denudation rates from the crustal cooling histories documented by thermochronologic techniques, especially in rapidly eroding terrains, since, in such cases, apparent deundation rates derived from thermochronologic data will usually overestimate true rates if the advective effect of denudation is not included. This is likely to be resolvable where the rate of denudation exceeds 300 m Ma^{-1} and when the depth of denudation occurring at these rates exceeds several kilometres prior to the sample cooling below the appropriate closure temperature. Because the time at which a sample cools below a particular closure temperature is relatively insensitive to advection, the initiation of denudation can be accurately established, even given uncertainties in the estimation of depths and rates of denudation. Where thermal events originate from a source within or below the lower crust, the cooling through denudation will dominate the low-temperature history of the shallow crust if denudation occurs coevally with the subsurface heating.

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INTRODUCTION

Relating short-term process studies to investigations of long-term landscape evolution necessitates a comparative knowledge of rates of change over short and long time-scales. Crucial to this requirement are data on long-term rates of denudation which may ultimately be compared with short-term rates from field investigations where the nature of surface geomorphic processes are known in some detail. Various techniques are now available for the estimation of long-term denudation rates; for instance, measurements of concentrations of a range of *in-situ*-produced cosmogenic nuclides in near-surface materials have recently yielded valuable insights into location-specific denudation rates (Nishiizumi *et al*., 1993; Bierman, 1994), although the age range over which rates can be estimated only exceeds one million years where denudation rates are virtually zero. Sediment volumes, either from interior basins or offshore accumulations, can provide a means of estimating regionally averaged mechanical denudation rates over time-scales in excess of 100 Ma (Poag and Sevon, 1989; Rust and Summerfield, 1990), but uncertainties over likely changes in sediment source areas over time greatly limit the extent to which such data can be used to infer detailed spatial and temporal patterns of denudation. This limitation, however, does not apply to thermochronologic techniques which, through establishing crustal cooling histories below particular ‘closure temperatures’ at specific locations, can provide estimates of regional variations in the timing, duration and rate of denudation over time-spans up to 100 Ma or more. Of the various thermochronologic techniques based on a range of radiometric systems with different ‘closure temperatures’, apatite fission-track analysis (AFTA) is overall the most valuable for geomorphic applications because its very low ‘closure temperature’ enables denudation of the upper few

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kilometres of the crust to be recorded (Roden and Miller, 1989; Brown *et al*., 1990; O'Sullivan *et al*., 1995; Tippett and Kamp, 1995).

The general principles involved in inferring denudation rates from AFTA data have been previously outlined by Brown *et al*. (1994a), while Gallagher (1995) has thoroughly examined the derivation of thermal histories from AFTA data, and Stüwe *et al*. (1994) have assessed the role of surface topography in perturbing critical isotherms (for steady-state conditions) and thereby influencing inferred denudational histories. Our aim here is to clarify some of the uncertainties involved in estimating ages, durations and rates of denudation from the cooling histories of rocks by examining, through simple thermal models, how the movement of rock towards the landsurface can perturb the thermal structure of the crust so as to bias denudation estimates, and by considering the problem of distinguishing the effects on crustal cooling of denudation and decay of transient thermal events. Although we consider thermochronologic techniques in general, we focus on the low-temperature thermochronology provided by AFTA.

The employment of this approach to derive quantitative information on denudation requires that data recording variations of temperature with time be transformed into data recording variations of depth with time. This transformation depends on knowing, or being able to make reasonable assumptions about, variations of temperature with depth within the crust, specifically at the time that cooling was recorded by the thermochronologic technique being used. This alone is a major source of uncertainty in estimating denudation rates because of the difficulty in constraining palaeogeothermal gradients from thermochronologic data (Bray *et al*., 1992; Howard and Foster, 1996). The process of denudation itself also influences the thermal structure of the crust by transporting rocks at depth upwards towards the earth's surface. This physical transport of heat (advection) increases the near-surface geothermal gradient, the magnitude and rate of increase being directly related to the rate of denudation. We analyse the thermal effects of regional crustal denudation, and discuss their implications for interpreting thermochronologic data.

ADVECTION OF HEAT AND ITS EFFECT ON THE RATE OF DENUDATIONAL COOLING

An assumption frequently made, either explicitly or implicitly, in many interpretations of thermochronologic data is that the crustal geotherm is not significantly affected by the denudation responsible for the cooling episode being measured. This assumption is often supported by the argument that rates of denudation implied by measured rates of cooling are sufficiently low that they do not affect significantly the thermal structure of the crust. To evaluate this assumption, we quantitatively examine the thermal effects of denudation using a simple one-dimensional thermal model with the aim of assessing the significance of these effects in deriving denudation rates from thermochronologic data.

The effect of denudation on the distribution of temperature (depths to isotherms) within the crust is illustrated in Figure 1 for a simple 'square pulse' denudational episode involving 10 km of denudation at a constant rate of 1000 m Ma^{-1} occurring over 10 Ma. The model (Brown *et al*., 1994b) demonstrates how the isotherms move upwards to shallower depths and become progressively more closely spaced as denudation proceeds, and then relax back towards their initial steady-state depths once denudation ceases. The assumption that the thermal structure of the crust remains stable during such a period of denudation will clearly introduce errors into the estimation of denudation rates based on thermochronologic data. Making this assumption implies that the isotherms remain static as denudation proceeds, so that a sample will pass through the array of isotherms reaching successively lower temperatures at a rate related only to the rate of denudation. If this assumption is relaxed then the isotherms move upwards in response to the advection of heat as denudation proceeds. This means that for a sample to cross a particular isotherm it has to move to a shallower depth, that is, move further than it would if the isotherms remained static (Figure 2).

Most radiometric ages are interpreted as a measure of the time since a sample last cooled below a particular 'blocking temperature' or 'closure temperature', that is, the time it crossed a particular critical isotherm (Clark and Jäger, 1969; Dodson, 1973; Purdy and Jäger, 1976; McDougall and Harrison, 1988; Hurford, 1991). The kinetics of diffusion suggest that this is an approximation since there is no single unique temperature above which no 'age' is recorded and below which all of the 'age' is retained (Harrison *et al*., 1985; Lovera *et al*., 1989; Baldwin *et al*., 1990). Nevertheless, the concept of unique closure temperatures for various systems provides an

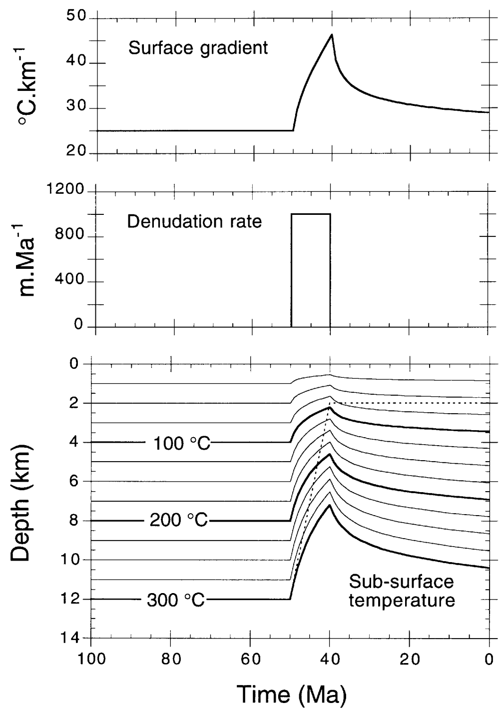

Figure 1. An illustration of the thermal effect of denudation and the resulting advection of heat which causes the isotherms to be 'dragged' upwards during the denudational episode before relaxing back towards their initial steady state. The example is for a simple 'square pulse' denudational episode at a rate of 1000 m Ma^{-1} and lasting for 10 Ma that removes 10 km of crustal section. The initial steady-state thermal gradient is 25°C km^{-1}. The model was generated using a numerical scheme described by Brown *et al*. (1994b). This is an extreme case which is representative of the high rates of denudation common in active compressional mountain belts.

effective first-order interpretation of thermochronologic data, and it is a useful means of examining the thermal effects of advection.

Advection of heat causes a delay between the time a sample reaches the depth at which the relevant critical isotherm was initially located, and the depth at which the sample actually crosses the isotherm (Figure 2). The magnitude of this time lag (ΔTime) and the additional distance that a sample must move in order to cross the critical isotherm (ΔDepth) are clearly important parameters in the estimation of denudation rates using thermochronologic data (Figure 2a). In general, the depth of any critical isotherm will always be overestimated if advection of heat is ignored, and this will consequently lead to an overestimate of the rate of denudation. The effect of the time lag is to compound this error. An additional measure of the effect of advection is the difference in temperature (ΔTemperature) measured at the initial depth of the critical isotherm (D_i) prior to a denudational episode (time = t_0), and at the time a sample reaches this depth (time = t_1) (Figure 2a).

The combined advective–diffusion heat flow equation (Carslaw and Jaeger, 1959) can be used to calculate the thermal effects of denudation with the rate of vertical advection, $\bar{U}_z$, representing the rate of denudation ($\bar{U}_x$ = 0 and $\bar{U}_y$ = 0):

$$\frac{\delta T}{\delta t} = \kappa \nabla^2 T - \mathbf{U} \bullet \nabla T \qquad (1)$$

A one-dimensional analytical solution to Equation 1 is provided by Carslaw and Jaeger (1959) for a homogeneous medium and a constant denudation rate U for t>0 and $0 < z < \infty$ with $T = T_0$ at $z = 0$:

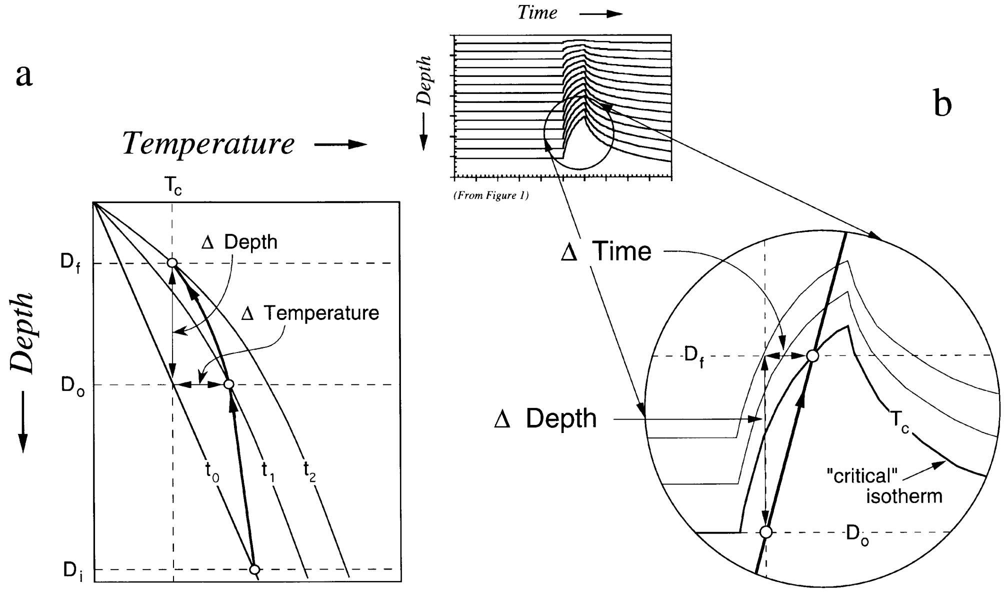

Figure 2. (a) A schematic diagram illustrating the thermal effects of denudation relevant to the cooling trajectory of a hypothetical sample collected for thermochronologic analysis. D_i is the initial depth of the sample, D_0 the initial depth of the 'critical isotherm' relevant to a particular thermochronologic system, and D_f the depth of that isotherm at the time (t_2) when the sample actually crosses it after the initiation of the denudational episode at time t_0. The hypothetical cooling trajectory is shown by the heavy black line. For any particular denudation rate the sample will move from D_i to D_0 at time t_1. However, heat is transported upwards as a result of denudation so the temperature at D_0 will have increased by an amount DTemperature at time t_1. In order to cool further, and thus cross the required critical isotherm, the sample must move a further distance, DDepth, to reach D_f, which it does at a later time t_2, before ultimately reaching the surface. The difference between time t_1 and t_2 represents the time lag or delay between the real time at which a sample cools to the critical isotherm temperature and the apparent time that would be calculated from the denudation rate without the advective effect of denudation (that is, assuming that the isotherms remain at their initial depths). The measured age of the sample is given by t_2, that is, the time taken for it to move from D_f to the surface. See text for a discussion of the relevance of these parameters. (b) The lag time, or delay (DTime), between reaching D_o and D_f is better illustrated by showing the hypothetical temporal cooling trajectory relative to the depths of the isotherms at various times.

$$T(t,z) = T_o + a(z - Ut) + \frac{1}{2} + a\left[(z + Ut)e^{(Uz/\kappa)} erfc\left(\frac{z + Ut}{2\sqrt{\kappa t}}\right) + (Ut - z) erfc\left(\frac{z - Ut}{2\sqrt{\kappa t}}\right)\right] \qquad (2)$$

where T is temperature, t is time, z is depth, U is the vertical denudation rate, *erfc* is the complimentary error function, a is the initial thermal gradient (25°C km^{-1} at time $t = 0$), T_0 is the surface temperature (0°C) and k is the thermal diffusivity (1×10^{-6} m^2 s^{-1}). In this model the surface is always at $z = 0$ with constant temperature T_0 and the initial uniform temperature gradient a at $t = 0$ persists from the surface at $z = 0$ to $z = \infty$.

This solution is valid for the region of interest, that is, shallow crustal depths of less than about 10 km, and the moderate amounts of denudation (0·5–10 km) examined here. However, for large amounts of denudation (> *c*. 10 km) or times exceeding *c*. 50 Ma, this solution overpredicts temperatures at depths greater than *c*. 10 km. An alternative analytical solution to Equation 1 for $0 < z < L$ is given by Wangen (1995) for the case where both the surface at $z = 0$ and the lower boundary at $z = L$ are held at constant temperature. However, Wangen's (1995) solution converges with Equation 2 where L is large (> *c*. 100 km) and only predicts significantly different results for amounts of denudation greater than *c*. 5 km when $L \leq$ *c*. 40 km (mean depth to the Moho).

The magnitude of DTime, DTemperature and DDepth (see Figure 2) for three isotherms (100, 200 and 300°C) at rates of denudation between 0 and 1000 m Ma^{-1} for different amounts of denudation ranging from 0·5 to 10 km (Figure 3a–c) were calculated using Equation 2 and, for comparison, using the solution of Wangen (1995) for $L = 40$ km. These three isotherms cover the range of closure temperatures for many of the commonly used thermochronologic techniques. The purpose of presenting the results of the calculations in this way is that,

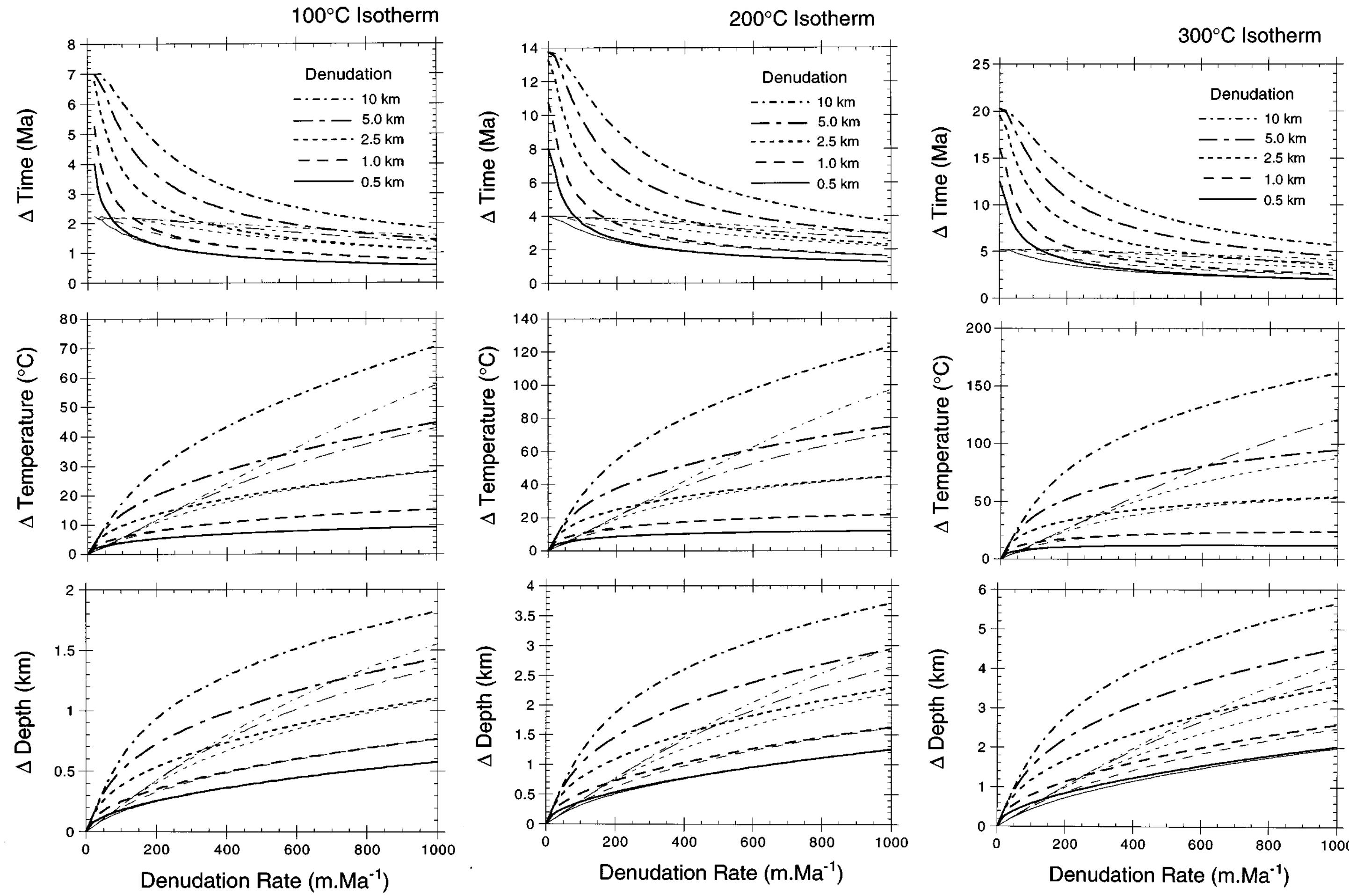

Figure 3. Plots of Δ Time, Δ Temperature and Δ Depth for a series of hypothetical cooling trajectories relative to three isotherms: (a) 100°C; (b) 200°C; (c) 300°C. The individual curves on the diagrams are for various depths (labelled in km) of denudation occurring at a range of rates from 0 to 1000m Ma^{-1}. The thick lines are the results obtained using Equation 2 and the thin lines are the results obtained using the solution given by Wangen (1995) with $L = 40$ km (see text for discussion). For a selected set of parameters the value of Δ Time can be compared with the uncertainty in the measured age estimate and the value of Δ Temperature can be compared with the uncertainty in the closure temperature of the relevant thermochronologic system. These measurements can then be used to assess whether the advective effects of denudation are likely to be significant for the relevant thermochronologic technique for the selected conditions.

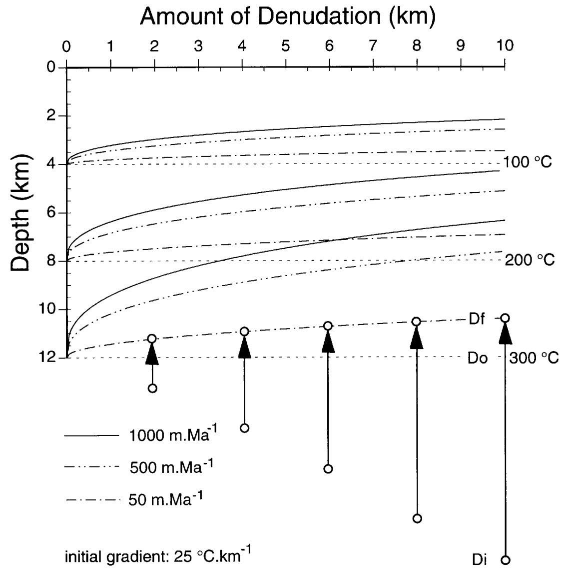

Figure 4. Plot of depth to the 100°C, 200°C and 300°C isotherms versus amount of section removed (for an initial steady-state gradient of 25°C km^{-1}). The isotherm depths are shown for three different denudation rates: 50, 500 and 1000 m Ma^{-1}. The initial depths to the steady-state isotherms were calculated using Equation 2 and are indicated by the thin dashed lines. The bold arrowed lines represent the paths of hypothetical samples which cross the 300°C isotherm (at 50 m Ma^{-1}) after the indicated amount of denudation has occurred

for any thermochronologic technique and for any denudational history, the magnitude of the predicted time lag (DTime) and the increase in temperature (DTemperature) at the depth of the critical isotherm concerned can be directly compared to, respectively, the expected uncertainty in measured age, and the uncertainty in the effective closure temperature for the system. Clearly, if the latter estimates are greater than the former, then the effects of advection are beyond the resolution of the termochronologic technique for those conditions. This, in turn, implies that an inherent uncertainty of DDepth must be included in any estimate of denudation calculated using thermochronologic data. Alternatively, if the magnitude of the advective effect is within the resolution of the technique, then there is some justification for attempting to use simple thermal models to estimate what these effects might be and to include these in denudation rate estimates. Kamp *et al*. (1989) used this approach in a thermochronologic study of the Southern Alps in New Zealand, where they made use of a two-dimensional thermal model proposed by Koons (1987) for the Alpine Fault region.

These calculations confirm the frequently made assumption that, under most circumstances, the effect of advection resulting from denudation is likely to be beyond the resolution of the majority of thermochronologic techniques. However, they do demonstrate the need to consider both the rate and duration (that is, amount of crustal section removed) of the denudational episode when deciding on what represents an appropriate threshold rate of denudation below which these effects can be ignored. For example, the often-cited value for this threshold of between 300 and 500 m Ma^{-1}, suggested by Parrish (1983, 1985), will generate uncertainties from less than 200 m to nearly 1 km on denudation estimates (and values of DTemperature of <5 to >30°C) depending on the duration of the denudational episode.

The relationship between the amount of section removed and the rate of denudation, and their combined effect on the depths to various isotherms, is shown graphically in Figure 4. Clearly, the effect of advection is greatest for high denudation rates and large depths of denudation. The important effect of advection, in this context, is that it always leads to an overestimation of the rate of denudation (based on thermochronologic data) if the calculations are made assuming a steady-state thermal gradient. This is illustrated by the curves of apparent versus true denudation rate, shown in Figure 5. The apparent rate was calculated by dividing the depth to the steady-state isotherm by the time taken for a hypothetical sample to reach the surface after crossing the actual depth of the isotherm, D_f (see Figure 2a) for various amount of denudation varying from 0·5 to 10 km. Of particular interest is the observation that the lag time will generally be only of the order of 1 to 2 Ma for most

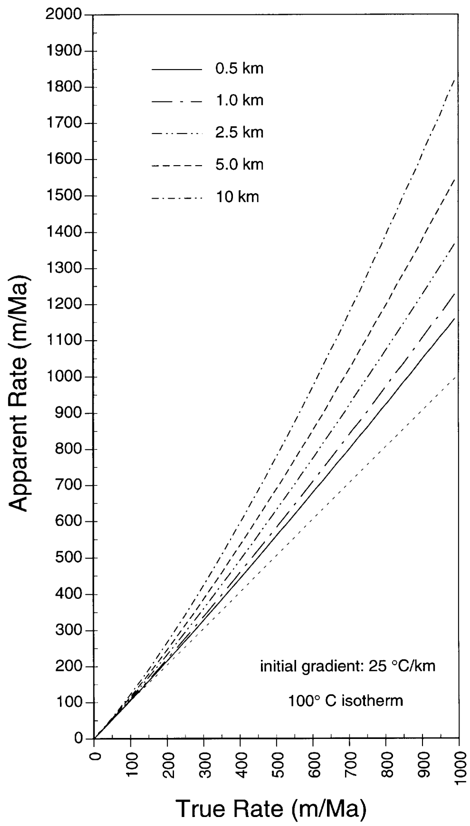

Figure 5. Plot of apparent versus true denudation rate. The apparent rates were calculated using Equation 2 and were derived by dividing the depth to the steady-state isotherm by the time taken for a hypothetical sample to reach the surface after crossing the actual depth (D_f) of the 100°C isotherm (see Figure 2a) after various amounts of denudation (from 0·5 to 10 km) had occurred at the appropriate true rate. The apparent rates represent the denudation rates that would be determined from thermochronologic data by dividing the steady-state depth to the relevant closure temperature (T_c) by the measured sample 'age'. The curves shown were calculated for the 100°C isotherm but are also appropriate for the 200°C and 300°C isotherms (for an initial steady-state gradient of 25°C km^{-1}).

conditions. This means that although estimates of the amount of denudation may be subject to large errors, estimates of the timing of denudation should be relatively insensitive to the rate of denudation, except, of course, where the event being measured is relatively recent (within the past few million years). Some relevant examples may include regions of the Southern Alps (New Zealand) (Koons, 1987; Kamp *et al*., 1989), the D'Entreauxcasteau Islands (Woodlark Basin, Papua New Guinea), the Greek Islands, and the Nanga Parbat area (Pakistan Himalaya) (Zeitler, 1985).

DENUDATIONAL COOLING VERSUS SUBSURFACE HEATING

The propagation of any subsurface thermal anomaly to the earth's surface will be primarily controlled by conduction, which is particularly inefficient at transferring heat within the crust, whereas the effect of denudation is to produce a relatively immediate cooling at shallow crustal levels. The immediacy of denudational cooling ensures that it is an efficient cooling mechanism capable of significantly moderating the effects of contemporaneous subsurface heating, at least at shallow crustal levels (< *c*. 10 km) (Brown *et al*., 1994b). Within tectonic environments where the initial steady-state geotherm is severely perturbed, such as within a duplex thrust stack or the proximity of large, shallow-level igneous intrusives, the transient thermal gradient will be highly unstable. Within this type of terrane it will be extremely difficult to resolve the

denudational cooling component of the thermal history on the basis of thermochronologic data alone (Hubbard *et al.*, 1991). By contrast, thermochronologic data can be expected to provide a valuable means of deciphering the denudational component of the net thermal history within thermal regimes where the crustal geotherm is not severely perturbed. The dilemma, of course, is that our understanding of the thermal stability (or otherwise) of various tectonic settings is based largely on interpretations of thermochronologic data themselves.

There is also the additional, but often overlooked, restriction that thermochronologic systems can generally only record episodes of *cooling*. The common practice of intepreting ages determined from thermochronologic data as recording 'thermal events' conveys the idea that the data are recording heating events (the implication being that cooling always follows immediately afterwards). This interpretation necessarily leads to models which require subsurface heat sources to explain the existence of the 'thermal event'. Consequently, discrete cooling episodes documented from thermochronologic data sets are often viewed as evidence for the existence of discrete heating events. In constructing geological models to explain the data, emphasis is thus most often placed on processes which can account for increases in thermal gradient rather than those which can explain crustal cooling. We do not dispute the fact that thermal gradients change, but we do suggest that many interpretations of thermochronologic data have overlooked or understimated the potential of denudation as a 'thermal event' (albeit in the inverse sense) capable of explaining the observed cooling.

The thermal sensitivity of AFTA makes this thermochronologic technique particularly prone to the effects of denudation, given that it responds to temperatures typical of the upper few kilometres of the crust (< *c*. 110 ± 10°C). In recent years, AFTA has been widely used to document low-temperature thermal histories within a wide range of different tectonic settings (Hurford, 1991). Data from these various terranes have proved to be of particular value in estimating denudation rates measured over geologically relevant time-scales (Brown *et al*., 1994a). Although many early studies focused on convergent mountain belts, much of the current AFTA data come from studies of continental rift margins. The fact that the youngest AFTA ages broadly coincide with the time of rifting in several, but not all, of the rift studies encouraged interpretations of these data which viewed the increased heat flow associated with extensional thinning of the crust as instrumental in resetting the apatite fission-track ages (Kohn and Eyal, 1981; Moore *et al*., 1986; Dumitru *et al*., 1991). The observed amount of cooling is thus seen as a consequence of denudation in conjunction with an elevated thermal gradient, with gradients as high as 40–50°C km^{-1} having been predicted by some studies. Available heat flow data from several rifts, however, indicate that heat flow along the subaerial rift margin is rarely significantly elevated above the background steady-state value (Morgan, 1983; Buck *et al*., 1988; Makris *et al*., 1991). There is also abundant geomorphic and offshore stratigraphic evidence which points to vigorous denudation of the evolving rift flanks, which may attain several kilometres in places. So while increased heat flow is certainly associated with rifting, it is, nonetheless, peculiar to the rift axis (the region of crustal thinning) and it seems unlikely that temperatures within the shallow crust of the rift margin would be significantly elevated. A fuller, quantitative analysis of the net effect of the competing processes of denudation and subsurface heating, and the efficiency of denudation in cooling the shallow crust, is provided elsewhere (Brown *et al*., 1994b).

DISCUSSION AND CONCLUSIONS

Outside of rapidly eroding mountain belts, the advection of heat accompanying denudation is unlikely to be significant in terms of deriving denudation rates from thermochronologic data. However, both the rate and the duration (total depth of denudation) of the denudational episode affect the magnitude of the errors introduced if advection is ignored, and both should be considered. Apparent denudation rates determined from thermochronologic data will generally overestimate the true rate if the effect of advection is not included. The degree to which this happens is a function of the rate of denudation and the amount of denudation that occurs *prior* to the time at which a sample cools below the relevant closure temperature. The advective effect of denudation is likely to be resolvable by thermochronologic techniques when the denudation rate exceeds *c*. 300 m Ma^{-1} and when the depth of denudation occurring at these rates exceeds several kilometres prior to the sample cooling below the appropriate closure temperature. The time at which a sample cools below a particular closure temperature is relatively insensitive to the effects of advection; 'the lag time' seldom exceeds *c*. 2 Ma for most geologically reasonable conditions. This implies that the onset of denudation can be accurately

determined from thermochronologic data despite the uncertainties associated with estimating depths and/or rates of denudation. Numerical modelling suggests that where the heat source is within, or below, the lower crust, the cooling effects of denudation will dominate the low-temperature thermal history of the shallow crust if regional denudation occurs coevally with subsurface heating.

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